

LCA Case Studies

Assessing Future Energy and Transport Systems: The Case of Fuel Cells

Part 2: Environmental Performance

Part 1: Methodological Aspects [Int J LCA 8 (5) 283 – 289 (2003)] • Part 2: Environmental Performance [Int J LCA 8 (6) 365 – 378 (2003)]

Preamble. This series of two papers which is based on a PhD thesis (Pehnt 2002a) discusses the assessment of fuel cells as future energy and transport systems from two perspectives. Part 1 analyses methodological issues associated with the future character of the systems and the need of forecasting process steps and uses the production of an SOFC stack as illustration. Part 2 presents the results of LCAs of fuel cells in stationary and mobile applications based on the methodology discussed before.

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Abstract

Goal, Scope and Background. Assessing future energy and transport systems is of major importance for providing timely information for decision makers. In the discussion of technology options, fuel cells are often portrayed as attractive options for power plants and automotive applications. However, when analysing these systems, the LCA analyst is confronted with methodological problems, particularly with data gaps and the requirement of forecasting and anticipation of future developments. This series of two papers aims at providing a methodological framework for assessing future energy and transport systems (Part 1) and applies this to the two major application areas of fuel cells (Part 2).

Methods. To allow the LCA of future energy and transport systems, forecasting tools like, amongst others, cost estimation methods and process simulation of systems are investigated with respect to the applicability in LCAs of future systems (Part 1). The manufacturing process of an SOFC stack is used as an illustration for the forecasting procedure. In Part 2, detailed LCAs of fuel cell power plants and power trains are carried out including fuel (hydrogen, methanol, gasoline, diesel and natural gas) and energy converter production. To compare it with competing technologies, internal combustion engines (automotive applications) and reciprocating engines, gas turbines and combined cycle plants (stationary applications) are also analysed.

Results and Discussion. Principally, the investigated forecasting methods are suitable for future energy system assessment. The selection of the best method depends on different factors such as required resources, quality of the results and flexibility. In particular, the time horizon of the investigation determines which forecasting tool may be applied. Environmentally relevant process steps exhibiting a significant time dependency shall always be investigated using different independent forecasting tools to ensure stability of the results.

The results of the LCA underline that, in general, fuel cells offer advantages in the impact categories usually dominated by pol-

lutant emissions, such as acidification and eutrophication, whereas for global warming and primary energy demand, the situation depends on a set of parameters such as driving cycle and fuel economy ratio in mobile applications and thermal/total efficiencies in stationary applications. For the latter impact categories, the choice of the primary energy carrier for fuel production (renewable or fossil) dominates the impact reduction. With increasing efficiency and improving emission performance of the conventional systems, the competition in both mobile and stationary applications is getting even stronger. The production of the fuel cell system is of low overall significance in stationary applications, whereas in vehicles, the lower life-time of the vehicle leads to a much higher significance of the power train production.

Recommendations and Perspectives. In future, rapid technological and energy economic development will bring further advances for both fuel cells and conventional energy converters. Therefore, LCAs at such an early stage of the market development can only be considered preliminary. It is an essential requirement to accompany the ongoing research and development with iterative LCAs, constantly pointing at environmental hot spots and bottlenecks.

Keywords: Cogeneration; combined cycle; fuel cells; gasification; gas turbine; hydrogen; methanol; Kvaerner CB&H process; life cycle assessment (LCA); polymer electrolyte membrane fuel cell (PEFC or PEMFC); power train; reciprocating engine; solid oxide fuel cell (SOFC); steam reforming

Introduction

In the preceding paper (Part 1, see Pehnt 2003a), methodological problems of assessing future energy technologies have been described. In Part 2, results from detailed LCAs of the stationary and mobile applications of fuel cells (Fig. 1) are reported. From the number of possible systems and system sizes, LCAs of domestic stationary applications as well as small portable systems are not reported here and will be subject of a future publication.

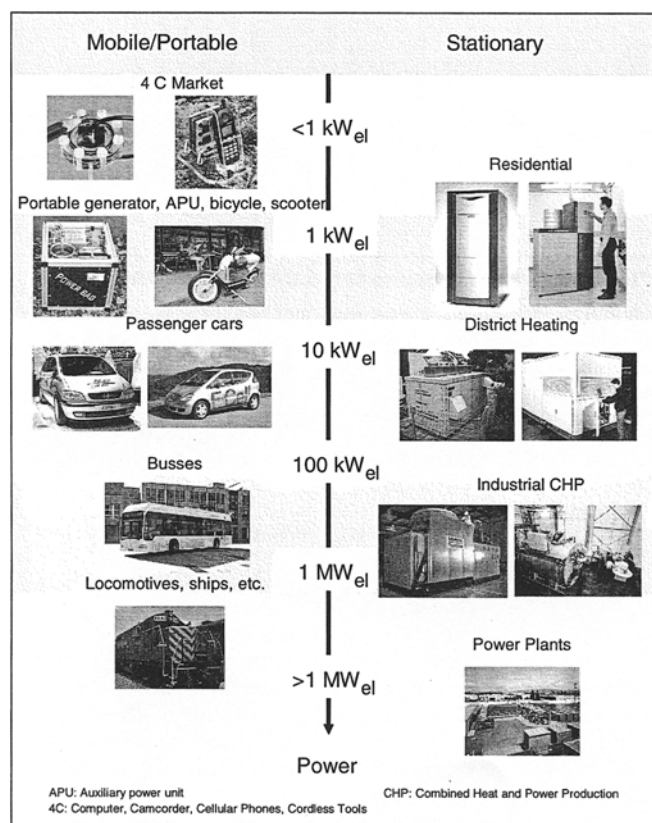


Fig. 1: Fuel cells in mobile and stationary applications

1 Goal and Scope Definition

1.1 Goal of the study

The goal of these LCAs is twofold: On the one hand, the principal ecological characteristics of fuel cells compared to future competing technologies shall be determined to support decision makers in terms of optimal applications of fuel cells and related fuels in the energy and transport sector. The second goal is to determine eventual environmental weak points along the life cycle of fuel cells.

1.2 Functional units

The LCA is structured according to the life cycle phases of the system. The corresponding functional units are

- **Fuel production:** Final energy carrier in MJ (lower heating value) at the fuel pipe of the plant (stationary application) or at the filling station (including environmental impacts of the tanking process)
- **System production:** Production of one kW_{el} fuel cell system, one stack and/or one vehicle/power plant
- **Mobile application:** One km transport in a compact sized passenger vehicle in a defined duty cycle
- **Stationary application:** One kWh_{el} at the user interface (low voltage for distributed power production; medium voltage for industrialised cogeneration). The heat produced in cogeneration systems is credited with a modern natural gas burner ('avoided burden'). That means that if the system produces x kWh electricity and y kWh heat simultaneously, the impacts of producing y kWh heat with a modern natural gas are subtracted from the total impacts, because this heat production is substituted by the cogeneration system.

For distributed generation, in addition, the functional unit 'Supply of a district with electricity and heat' is investigated which consists of the supply of a district heating system with heat and a defined amount of electricity. The results of this functional unit are reported in (Pehnt 2002a).

1.3 Systems to be investigated

The power conversion systems and fuels analysed here are indicated in Table 1.

Geographical coverage is Germany. To take into account the improvement potential of conventional power plants and power train technology, the year 2010 was defined as reference time.

Generally, a cradle-to-grave approach is selected. However, data for the disposal/recycling of fuel cell systems is limited. Recycling is considered applying the closed loop approach as suggested by ISO 14041. Infrastructure (e.g. power plant buildings, vehicle production or pipeline material) is considered.

Table 1: Investigated fuels, systems and impact categories in (Pehnt 2002a)

Fuels	Fuel cell systems	Conventional Systems
Natural gas	Passenger car: PEFC	Passenger car: Internal combustion engine
Biogas*	Distributed CHP: 200 kW _{el} PEFC	Distributed CHP: 200 kW _{el} reciprocating engine
Hydrogen from <ul style="list-style-type: none"> • natural gas • natural gas (Kværner CB&H) • biomass • electrolysis (renewable electricity) 	Industrial CHP: 3 MW _{el} SOFC Central power plant 20 MW _{el} (SOFC)	Industrial CHP: 3 MW _{el} gas turbine Gas combined cycle plant (600 MW _{el})
Methanol from <ul style="list-style-type: none"> • natural gas • biomass 		
Gasoline, diesel		
Future electricity mix		

CHP: Combined Heat and Power Production; CB&H Carbon Black & Hydrogen; PEFC Polymer Electrolyte Membrane Fuel Cell; SOFC Solid Oxide Fuel Cell; * not reported here

1.4 Impact assessment

The following impact categories are calculated and reported here:

- Use of non-renewable primary energy (in the following 'primary energy (nr)') with cumulated energy demand (based on the higher heating value of the fuels) as an aggregated impact parameter;
- global warming (GWP₁₀₀) using the IPCC factors (IPCC 1996);
- acidification and eutrophication as in (CML 1992);
- carcinogenic emissions from benzene, benzo(a)pyrene, particulate matter and formaldehyd taking unit risk factors from (UBA 1999);
- summer smog from MIR ('maximum incremental reactivity') factors as used in Californian legislation. As usually not all the components of NMHC emissions are known, the determined aggregated NMHC emission factors are multiplied by the specific reactivities as reported for different emission sources in (Acurex 1996, Höhle et al. 1996, Bach et al. 1998).

Site categories: Especially in the case of human and ecotoxic effects, it is not always reasonable to summarise all emissions of all life cycle steps into one value, since the environmental impacts may differ depending on the location of their release. Therefore, a methodology taking these site dependencies into account has to be used. In the cases of non globally effective pollutants, the balancing is done separately for three emission site categories. These categories represent areas of different population densities (see Borken et al. 1999); they are defined as follows:

- Site category I high population density (inner city; passenger car use, etc.)
- Site category II medium population density (agriculture, industrial estates, etc.)
- Site category III low population density or uninhabited (open sea, desert, etc.)

Based on these site categories, the emissions over the whole life cycles can be assessed separately for local (human toxicity, for instance), regional (acidification, eutrophication, summer smog), and global impacts (greenhouse effect, ozone depletion, resource consumption). Here, acidification, eutrophication and summer smog are calculated based on site categories I, II and 25% of category III, carcinogenicity is based on site categories I and II only, as argued in (Borken et al. 1999).

Note that the site categories are considered for the impact assessment only.

1.5 Normalisation

For the impact categories investigated, the data is normalised to the German daily impacts per capita ('person equivalents').

2 Mobile Applications: PEFC in Passenger Vehicles

2.1 Operation of fuel cell vehicles

Whereas for conventional vehicles based on internal combustion engines (ICE), the fuel combustion and the concomitant CO₂ emissions as well as the direct exhaust emissions from incomplete combustion and nitrogen oxidation are of relevance for the assessment of the use phase, for fuel cell vehicles, exhaust gas emissions are low (gasoline), almost (methanol) or entirely (hydrogen) zero with the important assumption that for fuel cell vehicles using gasoline or methanol as a fuel, cold start and evaporative emissions will be further reduced. Therefore, the question of the environmental characteristics of the use phase – apart from noise and land use which are not investigated here – is reduced to the question of the fuel consumption of these vehicles.

A number of parameters determine the fuel economy (Table 2). Of particular importance is the *driving cycle* chosen for the evaluation. With increasing stop and go or acceleration at high speeds, the fuel economy advantage of fuel cell vehicles decreases due to the relatively lower full load efficiency of fuel cell systems.

For the determination of the fuel economy advantages of fuel cell vehicles, also the characteristics of the *baseline ICE vehicles* are important. Whereas most of the American studies assume rather high fuel consumptions due to heavier vehicles and less efficient, oversized engines, gasoline consumptions assumed in the European studies are well below that (see Pehnt 2002b for a review of several LCA studies and underlying assumptions). In these studies, mainly future improved gasoline or diesel vehicle concepts are considered which are demonstrated on the market already, but which have not yet diffused into the market on a large scale. For instance, for a compact sized car, the 3 l/100 km (1 MJ/km) vehicle is state of the art but far from average fuel economies. For the reasons summarised above, most European studies calculate significantly lower fuel economy advantages.

Table 2: Main parameters for the determination of the fuel consumption of fuel cell vehicles

Parameter	Subparameter	Comments
Mechanical energy demand	Mass	– Can be reduced e. g. by light weight materials – Consider weight of power train, incremental weight of fuel cell system
	Rolling resistance	
	Air resistance	
Driving characteristics/ driving cycle		– More dynamic driving cycles lead to shifts in favor of ICEs
Efficiencies of system components	Polarization curve	– Operation point is important: Offset between maximum efficiency and maximum power
	Reformer (MeOH)	
	Parasitic loads	
Power management	Battery, supercapacitors	– Avoid full load or idle operation – Improves cold start characteristics
	Brake energy recovery	

In this study, the fuel cell car is a compact size cars with 750 kg base weight as defined in detail in (Pehnt 2002a), with calculations from (Carpetis 2000). The driving cycle consists of urban and extra-urban parts according to the New European Driving Cycle and, additionally, of a highway part. Assuming an optimistic, but realisable fuel cell system efficiency curve, a hydrogen consumption of 1.03 MJ/km (in the case of hydrogen as fuel) and a methanol consumption of 1.26 MJ/km for methanol fuel cell cars are calculated. The direct emissions are almost negligible.

2.2 Production of the fuel

For fuel cell applications, mainly two fuels are of interest for mobile applications: hydrogen and methanol. Specific aspects of their life-cycles are discussed in the subsequent sections.

2.2.1 Hydrogen

Roughly 48% of the world wide hydrogen production is accomplished by steam reforming of natural gas, 30% by processing crude oil products, 18% by processing coal and 3% as a byproduct of the chlor-alkali process. However, a number of more innovative production paths exists, such as the Carbon black and hydrogen process developed by Kværner AS with parallel carbon black production, electrolysis from various electricity sources, or gasification of biomass. In addition, CO₂ sequestration or the commercial use of CO₂ have been mentioned as ways to lower GHG emissions from H₂ supply.

Steam reforming. Here, efficiencies, emission factors and infrastructure requirements from steam reforming plants of the German Lurgi GmbH are considered as reference for the hydrogen production from natural gas. The production process is shown in Fig. 2A. A process efficiency of 81% (lower heating value) can be achieved if the energy content of the coproduced process steam is taken into account. Environmental impacts resulting from the coproduct are considered by including a process steam boiler into the process boundaries. Process steam provided by the steam reformer has then been assumed to substitute conventionally produced steam together with its related environmental impacts.

A hydrogen compression to 80 bar is considered for hydrogen transportation in a local hydrogen network to the fuel stations.

The Kværner Carbon Black & Hydrogen (CB&H) process. This process is based on the decomposition of gaseous hydrocarbons into hydrogen and carbon black within a plasma gas, ignited by an electric arc. The production process yields hydrogen as the target product and carbon black as coproduct. Natural gas has been chosen as hydrocarbon raw material.

Electricity and natural gas, boiler feed water, nitrogen, graphite and construction materials are included as inputs of the process. Apart from hydrogen and carbon black, process steam is produced and small amounts of pollutants are emitted by the process, resulting from incomplete pyrolysis reac-

tions and impurities in the feed gas. Detailed data was provided by the company.

A German location of the hydrogen production facility is chosen to allow an easier comparison of Kværner and steam reforming processes. Electricity for pyrolysis is delivered by a combined cycle power plant and natural gas is represented by the average German high pressure gas mixture. In a sensitivity analysis, various other electricity sources are evaluated but not reported here.

Since the carbon black could not directly be used within the original system boundaries, the boundaries were extended to enclose a conventional carbon black production process. Now, the amount of carbon black produced by the Kværner process can be assumed to substitute the same amount of conventionally produced carbon black, and to reduce the environmental impacts of the carbon black production process.

Water electrolysis. A progressive electrolyser, working at 80°C with a process pressure of 30 bar, is the basis for calculating the environmental impacts of the production process. Electricity demand is estimated to 4.35 kWh per Nm³ H₂ produced, which includes peripheral consumers like lye pumps and control equipment. Construction materials, deionized water, lye and electrode consumption are considered for the assessment of the environmental impacts. The electrolyzers are situated either close to the source of electric energy or – in case of high voltage direct current (HVDC) transportation – close to fuel stations. Several electricity sources are evaluated for the H₂ supply. Here, only a German hydroelectric power plant is reported.

Distribution of H₂. For transportation of H₂ three possibilities are assessed: pipeline transport from the production country only, shipping of liquified hydrogen, and HVDC transportation. The shipping concept is adopted from the Euro-Quebec Hydro-Hydrogen Pilot Project (EQHPP) where a hydrogen barge carrier – a cargo ship which does not carry the liquefied hydrogen in built-in tanks, but the complete transport containers (barges) instead – is assumed to minimize the losses during tank filling. During transportation, hydrogen losses due to evaporation are estimated to be below 0.1% per day. The propulsion energy for the barge carrier is delivered by a diesel engine fueled with heavy oil or, alternatively, with H₂.

To determine the necessary energy for hydrogen liquefaction, an extrapolation of existing liquefying plants leads to a specific energy demand of 0,65 kWh/l H₂. The source of the electric energy is assumed to be the same as the one for the electrolyzer. The supply of liquid hydrogen from the harbour to the fuel stations is carried out by road trailers, with a capacity of 3.5 tons hydrogen each and an average diesel consumption of 0.344 J per MJ hydrogen and km.

The supply of gaseous hydrogen at the filling station requires compression to high pressures. For that purpose, compressors powered by electrical engines are used.

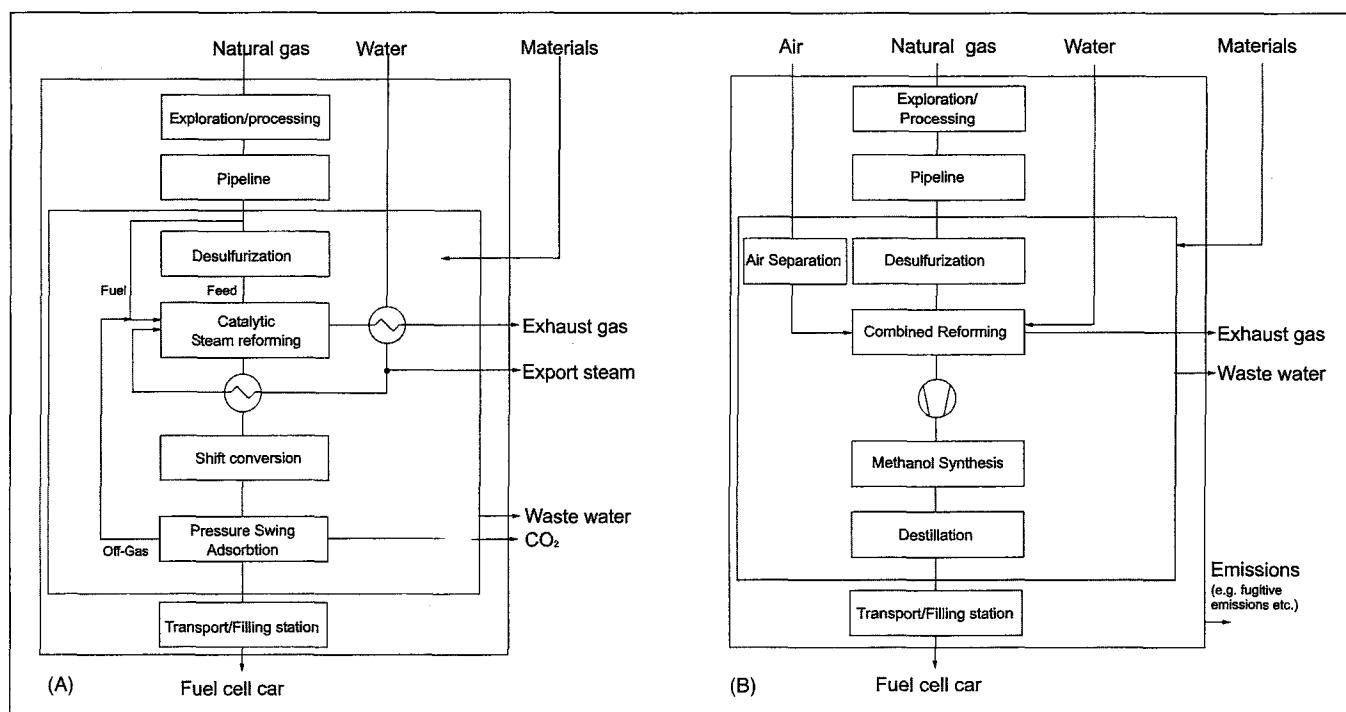


Fig. 2: Example of two fossil fuel chains: steam reforming of hydrogen (A) and combined reforming of methanol from natural gas (B)

2.2 Methanol

Methanol is under consideration as a 'liquid hydrogen storage'. Today, it is a chemical commodity mainly produced from natural gas.

Combined reforming. If produced from natural gas, the efficiency of the methanol conversion plant is of main importance for the overall impact, especially for the primary energy demand and the greenhouse gas emissions. Efficiencies of average plants (LHV methanol/LHV natural gas) are well below 65% leading to CO₂ emissions in the order of 30 to 40 g CO₂/MJ LHV methanol, whereas modern plants will achieve efficiencies higher than 65% depending on the process layout (e.g. use of oxygen) and, consequently, the investment costs.

In this study, data from one of the major methanol plant suppliers is used. Natural gas, boiler feed water, and nitrogen are included as inputs of the process (Fig. 2B). In addition, detailed data on required construction materials was available. The LHV average efficiency of that plant is 66% consistent with the combined reforming Statoil plant in Norway as well as future plants. In the methanol LCA, a mixture of methanol produced in Norway and Russia is assumed. This assumption is necessary because – unlike the crude oil market – no clear supply structure of methanol as a fuel has developed in Europe at this point. In future, however, locations closer (Netherlands) as well as further away can contribute to the European methanol supply so that the assumption should be a good approximation to future developments. The distances are adjusted to the supply of German filling stations.

Biomass gasification. Methanol can also be produced using biogen synthesis gases, such as from gasification of wood or biowaste, anaerobic digestion or CO₂ absorption from air

(with additional H₂ input). Technical data of these supply paths is scarce: efficiency numbers are often in the range of 40% for biomass gasification. In this study, the Biometh process with data from (Hasler et al. 1993, Lurgi 1993, Hasler et al. 1995) is assessed. This process is special in so far as a large portion of the synthesis gas produced is combusted in a reciprocating engine with concomitant electricity and heat production to achieve an appropriate stoichiometric ratio for methanol synthesis. The associated impacts of the process are allocated to the three products methanol, electricity and heat according to the exergy.¹

2.3 Production of the vehicle

The LCA of fuel cell stack production was carried out using industry data for materials (platinum group metals (PGM) from South Africa, natural and synthetic graphite, membrane, PTFE and others) and for the stack production as supplied by the major PEFC manufacturer Ballard for future stacks with reduced PGM loading. A PGM recycling rate of 75% was assumed for the base case (see chapter 2.6). Further details of the materials LCA can be found in (Pehnt 2001b, Pehnt 2002a).

Due to the early stage of development, the balance-of-plant materials could only be roughly estimated. Of particular importance are the PGM for catalyst materials in the stack, the reformer and an eventual Pd/Ag membrane for gas clean-up (with methanol as a fuel). The production of the car body and the conventional vehicle is taken from (Schweimer 1999).

¹ In a sensitivity analysis in (Pehnt 2002a), a credit is also given to the coproducts. This alters the results, but does not change the conclusions of the LCAs.

2.4 The conventional competitors

Future developments will also focus on optimising conventional vehicles. More stringent emission levels in many nations lead to intensive research in the optimisation of ICE vehicles. Catalysts and emission control systems, direct injection, downsizing/supercharging, and valve control are only a few examples of future ICE development. Therefore, LCAs should consider this future improvement potential and compare fuel cell vehicles not only to average ICE vehicles, but also to future car generations.

Here, we assume a modestly improved future 5 l/km gasoline combustion engine vehicle (ICEV) (1.6 MJ/km) with optimised catalyst technology using the same driving cycle and assumptions regarding the vehicle parameters as for the fuel cell car. The emissions of the vehicle conform to the Euro 4 emission standard for European cars which will be mandatory from 2005 on.

In the case of hydrogen internal combustion engines, we assume a slightly higher efficiency resulting in a fuel consumption of 1.52 MJ/km and emissions as derived in (Ifeu 1999).

2.5 Data quality

The data quality for the fuels and the production of the car body, the combustion engine and the stacks is high with some uncertainties regarding reduction of energy demand due to large-scale production processes. The balance of plant (reformer, gas cleanup, ...), however, could only be estimated due to the early stage of development for series production of these systems. The fuel consumption is based on model calculations. Therefore, a complete LCA should be repeated once the first series products and measured data for fuel consumption are available.

2.6 The total picture

In the following, the results from the different life cycle stages are put together to obtain a complete picture of the performance of the different power train and fuel options (Fig. 3). For the fuel cell applications in passenger cars, the fuel, especially the primary energy carrier, is the main parameter for results in the environmental impact categories 'use of non-renewable energy resources' and 'global warming'. Although the tank-to-wheel efficiency of a fuel cell power train using hydrogen is almost twice as high as that of a future gasoline internal combustion engine (ICE) based on the model used, the use of fossil hydrogen in fuel cells leads to a reduction of global warming of 15% only compared to the future gasoline ICE. This relatively low advantage of fuel cells for this impact category results from the lower efficiency of hydrogen production compared to gasoline, but also from the more environmentally intensive production of the fuel cell vehicle which has, for the first time, been assessed in detail in this research (see below). The results show that, assuming a recycling rate of 75% of the catalyst materials, 25 to 30% of global warming and 65 to 70% of acidification are caused by the production of the vehicle. The production of a fuel cell vehicle for

various impact categories is twice as environmentally intensive as that of an internal combustion engine vehicle.

Clear advantages of the (fossil) hydrogen fuel cell vehicle over the conventional car lie in the reduction of acidification (–25% compared to future ICE with 'Euro 4 emission standards'), eutrophication (–43%), summer smog (–76%) and the emission of carcinogenic substances (–86%). However, only the transition to hydrogen produced from renewable primary energy carriers or the innovative use of by-products of hydrogen production (such as carbon black from the Kværner carbon black and hydrogen process) efficiently reduces resource consumption and global warming. In renewable hydrogen scenarios, attention has to be paid to the transport and distribution of hydrogen which contributes significantly to acidification and eutrophication.

However, the H_2 can also be used in ICE vehicles. These vehicles have comparable efficiencies to gasoline ICE engines, and, therefore, lower efficiencies than fuel cell vehicles. The exhaust emissions of these vehicles are significantly lower (criteria pollutant without NO_x) or lower (NO_x) than in conventional ICEs. On the other hand, their production is less environmentally 'costly'. The competition of ICE in this impact category thus remains a challenge for fuel cell vehicles.

Due to the higher number of conversion steps and the increased weight of the vehicles, the use of methanol produced from natural gas increases energy and resource consumption and does not reduce the greenhouse gas emissions compared to future gasoline ICE vehicles. Advantages are found in the other impact categories which are dominated by the exhaust emissions of the conventional vehicles (e.g. acidification and summer smog), although the methanol fuel cell car is not a 'zero emission' vehicle. The reduction of impacts is, however, less pronounced than in the case of hydrogen as a fuel.

The use of biomethanol in fuel cells as well as in the ICE leads to a clear reduction of global warming and non-renewable energy resource consumption. The use of bio-primary energy carriers does not, however, automatically reduce all impact categories. The supply of wood, for instance, leads to an increase in carcinogenic emissions from offroad equipment of the wood supply (see below). Additionally, the biomethanol process analysed here increases acidification and eutrophication due to the combustion of purge gas which is needed to increase the concentration of H_2 in the synthesis gas. Alternative ways to increase the H_2 content are thus recommended. A large-scale application of biomethanol in Germany is, however, restricted by the limited energy potential of biomass and the competition with the use in stationary applications.

Apart from the biomass based fuel chains, carcinogenic emissions mainly occur in the Diesel engine. For the particle emission level, the Euro 4 emission standard was chosen as a basis. It has to be recognised, however, that the Euro 4 emission standard is quite strict and, therefore, the absolute emission level is low.

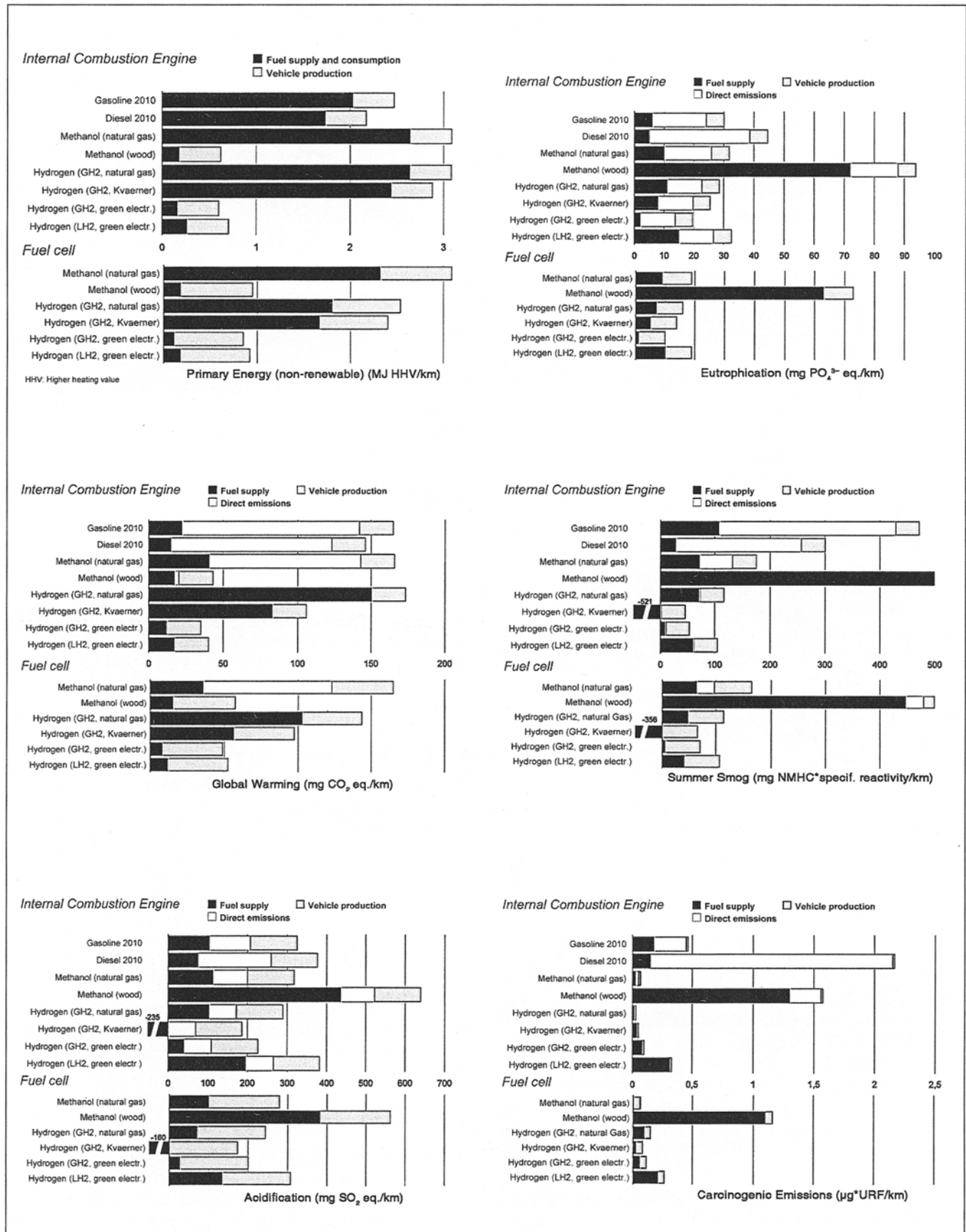


Fig. 3: Environmental impacts of different power train and fuel options per km in a New European Driving Cycle plus highway part.

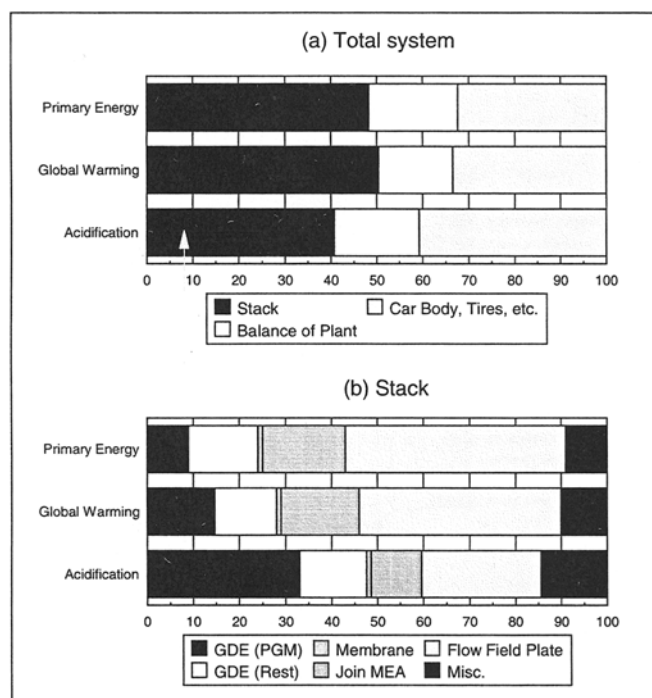


Fig. 4: Production of a fuel cell vehicle based on methanol: Contribution of components to primary energy (non-renewable), global warming and acidification. Assumption: 75% platinum group metals (PGM) recycling

To further investigate the production of fuel cell vehicle, Fig. 4 shows the contribution of different components of the vehicle to the total impacts of producing one vehicle assuming that 75% of the catalyst materials are recycled. It is obvious that the car chassis, tires, etc. contribute similar environmental impacts as the production of the stack. The balance of plant is of less importance. However, this is partly due to the fact that only a streamlined LCA of the balance-of-plant could be carried out.

Analysing the contribution of the stack production further (Fig. 4b), two components turn out to be of special relevance. The gas diffusion electrode (GDE) is responsible for a large share of the total acidification and, to a lesser degree, the global warming gas emissions. The crucial materials causing the high acidification are the platinum group metals (PGM) used as catalysts. PGM are mainly produced in South Africa (68% of the world platinum supply and 75% of the world rhodium supply) and as a by-product of nickel mining in Russia. Even in the modern African mines, the mining of PGM results in significant environmental interventions particularly because of the SO_2 emissions along the production chain. Part of the SO_2 is emitted during the pyrometallurgical treatment of the material. The tailings of the mining also act as potential sulfur sources even though, in arid regions such as South Africa, the tailings are less relevant with respect to SO_2 emissions. Methodological questions associated with the LCA of PGMs are discussed in (Hochfeld 1997, Schuckert et al. 1998).

The flow field plate is the second important component, particularly because of the electricity input for resin impregnation of the plate. Higher throughputs for series production have been assumed in this LCA. Even higher produc-

tion volumes could further reduce the specific energy consumption. It is interesting that the graphitic materials, commonly considered as a main ecological factor, contribute less greenhouse gas emissions to the total than the electricity consumption. This is also a result of the efforts to reduce the weight of the flow plates.

Improvement potentials as identified in (Pehnt 2001b) include the reduction of PGM loading (the lower limit of the loading is determined by the feasibility of recycling and the loss in performance; note that as soon as a rapid, global introduction of fuel cells occurs, recycling becomes a main issue also because of the resource situation (Råde 2001), maximizing the PGM yield during production (selective deposition of the catalyst ink and waste minimization by alternative cutting procedures such as laser cutting and optimized GDE geometries), recycling of catalysts and components, and using 'greener' electricity. An efficient recycling system has already been established in automobile exhaust catalyst recycling. Recycling catalysts can reduce the environmental impacts for PGM production by a factor 20 (primary energy demand) to 100 (SO_2 emissions) (Schuckert et al. 1998). It has to be mentioned that the 'recycling rate' not only considers the technically feasible platinum recovery, but also depends on a number of additional factors, such as the economic incentive (depending on the PGM price), the availability of recycling infrastructure, the export quota to countries without such infrastructure (e.g. about one third of the German decommissioned vehicles is exported to Eastern European countries) and the distribution of PGM in the fuel cell. It is likely, however, that due to the much higher PGM use in fuel cell cars, recycling will be mandatory. This could be reinforced by measures such as deposits which ensure a high return rate.

3 Stationary Systems

Fuel cells can be applied in various stationary applications (Fig. 1), ranging from one kW_{el} systems for domestic heating, combined heat and power production (CHP) for district heating or large buildings, up to MW applications for industrial cogeneration and electricity production without cogeneration (Pehnt and Ramesohl 2003). In each of these applications, different conventional systems are already well established, e.g. gas engine CHP, gas turbines or combined cycle power plants. The environmental assessment must, therefore, distinguish between the applications and compare fuel cells to different competitors.

In the following, PEFC in district heating systems and SOFC in industrial cogeneration and pure electricity generation will be analysed.

3.1 Operation of fuel cell power plants

The operation of SOFC and PEFCs leads to minimal direct emissions due to relatively low (compared to combustion engines or turbines) operating temperatures (for thermal NO_x emissions) and gas cleanup requirements (e.g. the required SO_2 removal). The emissions were deduced from average emissions from reformer burners.

Essential for the LCA of the systems are the assumed electrical and thermal efficiencies (Table 3). For all systems, careful estimations for future developments of efficiencies and emissions were made based on literature data, expert interviews and measured data from existing, modern plants. The simultaneously produced heat in combined heat and power systems was credited with heat from a modern natural gas burner so that the environmental impacts refer to 1 kWh electricity output ('avoided burden approach').

Referring to natural gas as a fuel, in the low power range, PEFC are assumed to have electrical efficiencies in the order of 28 to 35% for house heating systems and 40% in the 100 kW_{el} range. The latter value has not been achieved in pilot plants so far but is projected for future systems. In some systems, especially of the early generations, however, degradation effects lower the 'lifetime efficiency' substantially.

High-temperature fuel cells offer efficiencies of 50% when used in lower power regimes. 47% have already been demonstrated in several demonstration systems. In future, coupling fuel cells with gas turbines to use the exhaust heat promises efficiencies of up to 68% at the beginning of the operation, with expected degradation to 62–64% at the end of the life.

It is worth mentioning, however, that even in the 3–10 MW power regime, the efficiencies of fuel cell systems would exceed those of large combined cycle power plants in the 100 MW range.

For systems operated not with a fixed operation point, but with variable load, the efficiency as a function of the load is of relevance as well. The PEFC was modelled using average load data from a district heating system. As long as the system does not fall below a certain minimum power, the elec-

trical efficiency increases with decreasing load. Similar to the driving cycle in the mobile application, therefore, the application dependent load characteristics should be considered. High-temperature fuel cells will, however, mainly be operated at fixed operating conditions.

The thermal efficiency is, of course, a function of the temperature of the heat medium. If only steam is needed as in many industrial applications, it will be lower than for a low-temperature district or house heating system. Also, the thermal efficiency is a function of the load. Generally, current target values for most fuel cell systems are approximately 80% total efficiency.

3.2 Production of the fuel

Natural gas. In the near and midterm future, natural gas will be the fuel of choice for stationary applications. The life-cycle of natural gas comprises the exploration and extraction, the processing and transport to the consumer. In this study, an adaption of (ESU 1996) (future import mix, reduced methane leakage according to Dedikov et al. 1998) was used.

Allothermal gasification. For longterm applications, biogen and other renewable fuels are considered suitable for the use in fuel cells. Options include gasification of wood and other biomass, anaerobic digestion of biowaste, sewage, manure, etc. Here, the allothermal gasification of wood was assessed using a pilot-scale plant developed by DMT Essen.

In addition, in (Pehnt 2002a), **anaerobic digestion** of biowaste is investigated and will be subject of a separate publication.

Table 3: Efficiencies (averaged over life time) and emissions of the assessed electricity production systems

	Power (kW _{el})	Electrical efficiency (%)	Thermal efficiency (%)	Emissions	Remark
PEFC	200	41	37	From PAFC operation	Determined by system simulation for district heating application
Engine CHP	200	32	60	1/3 old TA Luft (CO, NO _x) (German legislation) and empirical data	Determined from modern operating engine CHPs and (Ifeu 1999, IKARUS 1994, Stein 1998)
SOFC (industrial cogeneration)	3000	57	23	From PAFC operation	Hybrid system with gas turbine
Gas turbine	3000	39	36 *	Low-NO _x combustion chamber	Determined from modern operating gas turbines and (GEMIS 2001, Heinisch and Trumpf 1998, Hella_KG 1999)
SOFC (no cogeneration)	20.000	65	–	From PAFC operation	Hybrid system with gas turbine
Gas Combined Cycle (CC)	600.000	58	–	Empirical data	Determined from modern operating CC power plants and (Dones, Gantner 1996, Neubrandenburg 1999).
Future German electricity mix 2010					Scenario based on (Prognos 1998)

Efficiencies based on LHV. * Heat output as process steam

3.3 Production of the power plant

3.3.1 PEFC

For the production of PEFC power plants, an LCA according to the future Ballard 200 kW_{el} system was carried out using industry data for the stack production and estimated data for the composition of the balance-of-plant (Pehnt 2001b, Pehnt 2002a). Due to the higher catalyst loading and the limited number of systems, a higher PGM recycling rate of 90% was assumed.

3.3.2 SOFC

Manufacturing SOFCs involves a number of rather unconventional materials such as ZrO₂, Ni, rare earth compounds and, depending on the concept used, further materials such as chromium for bipolar plates (in the case of the planar concept). Here, the stack and balance-of-plant production according to the Siemens planar design as shown in Part 1 (Pehnt 2003a; Fig. 1) of this publication was assessed. For the materials, data from the industrial suppliers was available.

3.4 The conventional competitors

Conventional systems are constantly optimised. In the US advanced turbine programme, for instance, gas turbines in the MW range have reached electrical efficiencies of more than 40%. Also, combined cycle plants reach average efficiencies of 58–60%, with 65% (without degradation) being forecast by some researchers. This means that the competition is getting tougher. Here, a detailed survey of future trends in power plant technology led to the reference data as given in Table 3.

In addition, improved 3-way catalysts for reciprocating engines, low-NO_x combustion chambers and other primary and secondary measures for gas turbines as well as NO_x and SO₂ abatement technologies for large power plants have

strongly reduced the exhaust emissions. In the definition of the emission factors, these future developments were taken into account.

For combined heat and power production, the thermal efficiency is of importance as well. The thermal efficiencies of conventional systems have been a key parameter for past optimisation of the systems. Gas engines, for instance, can reach total efficiencies of above 90% total efficiency. Combined cycle CHP plants can also achieve thermal efficiencies of 50% resulting in total efficiencies of nearly 90%.

3.5 Data quality

The data quality for fuel production is high. The performance data is partly based on model calculations and target data and must therefore be validated at a later stage of fuel cell development. For the conventional systems, performance data from a number of existing, modern plants is used. The LCA of fuel cell production is based on industrial information and additional assumptions regarding large-scale production processes with a rather high uncertainty. However, the relative importance of plant production is significantly lower than in the mobile applications.

3.6 The total picture

3.6.1 Systems operated with fossil fuels

In Fig. 5, different environmental impacts of fuel cell energy production including all life cycle stages compared to competitors are represented based on non-renewable fuels. Note that in order to present the numbers in one diagram and in order to show the specific importance of the respective environmental impact, the values were normalised by dividing by the daily environmental impact per capita ('person equivalents').

In industrial combined heat and power production (CHP) and central electricity production, Solid Oxide Fuel Cells

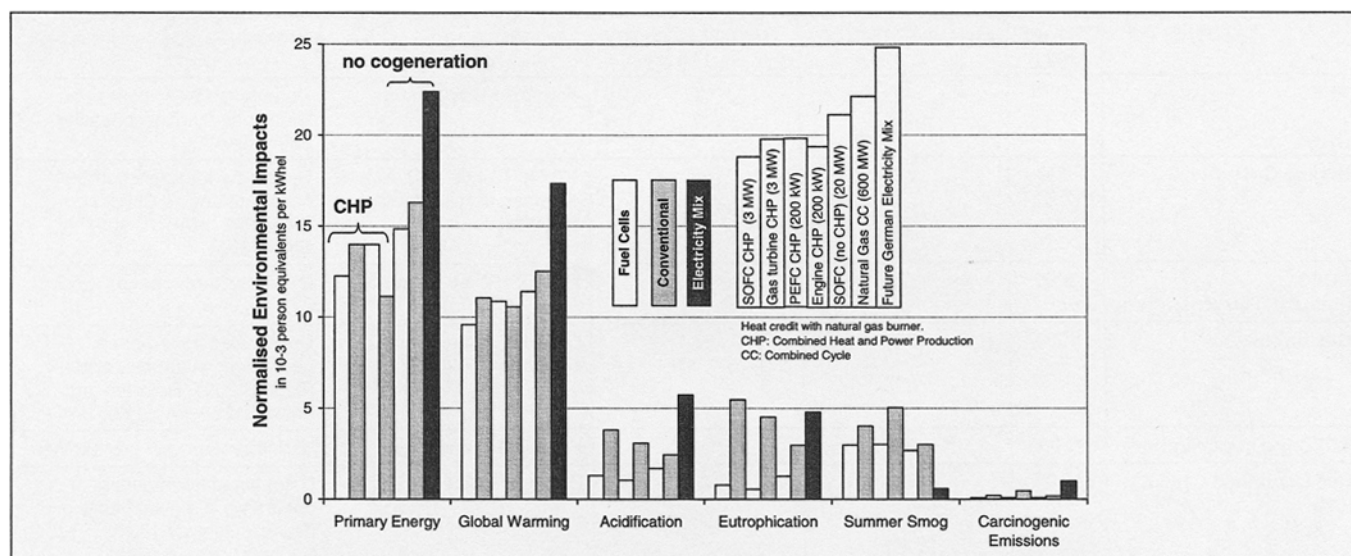


Fig. 5: Normalised results of LCAs of different electricity generating systems (non-renewable fuels) for various impact categories (functional unit: 1 kWh_{el}). If heat is co-produced it is credited with a modern natural gas burner ('avoided burden'). All data is normalised to person equivalents by dividing the impacts by the average daily per capita impact in Germany. (10×10^{-3} person equivalents equal 4.93 MJ primary energy (non-renewable); 361 g CO₂ eq.; 1.46 g SO₂ eq.; 0.153 g PO₄³⁻ eq.; 0.625 g NMHC; 2.54 e-6 g Unit risk factor weighted carcinogenic emissions)

(SOFC) are in almost all impact categories superior to both conventional competing technologies and the future (2010) German electricity mix (see Fig. 5). The use of non-renewable energy resources and the global warming are reduced by 9 to 13% compared to conventional modern technologies and up to 45% compared to the electricity mix.

In decentralised CHP for district heating applications (power range 200 kW_{el}, PEFC technology), the use of energy resources is slightly higher than that of the competing future engine power plant due to the lower overall efficiency (see Fig. 5). The greenhouse gas emissions from the two systems are almost equal. Therefore, focus of future development of fuel cell power plants should be on increasing the thermal efficiencies, for instance, by using the heat of condensation and optimising the use of the exhaust heat of the reformer burner.

In the case of local emissions and related impact categories (e.g. acidification), fuel cell power plants allow reductions ranging from 40% (summer smog) to 88% (eutrophication). Unlike engine CHP plants, fuel cells couple the advantages of reduced energy consumption compared to separate heat and power production with low direct emissions.

For example, the SOFC produces 70% less acidification on a life-cycle basis than a low-NO_x gas turbine and 30% less than a modern natural gas combined cycle plant. The acidifying emissions in the case of SOFCs stem almost exclusively from the energy chain and the production of the system (Fig. 6). For gas turbines, in contrast, the direct NO_x emissions account for more than 50% of total acidification.

At the same time, a gas turbine in the 3 MW_{el} power range produces less greenhouse gases than an SOFC without

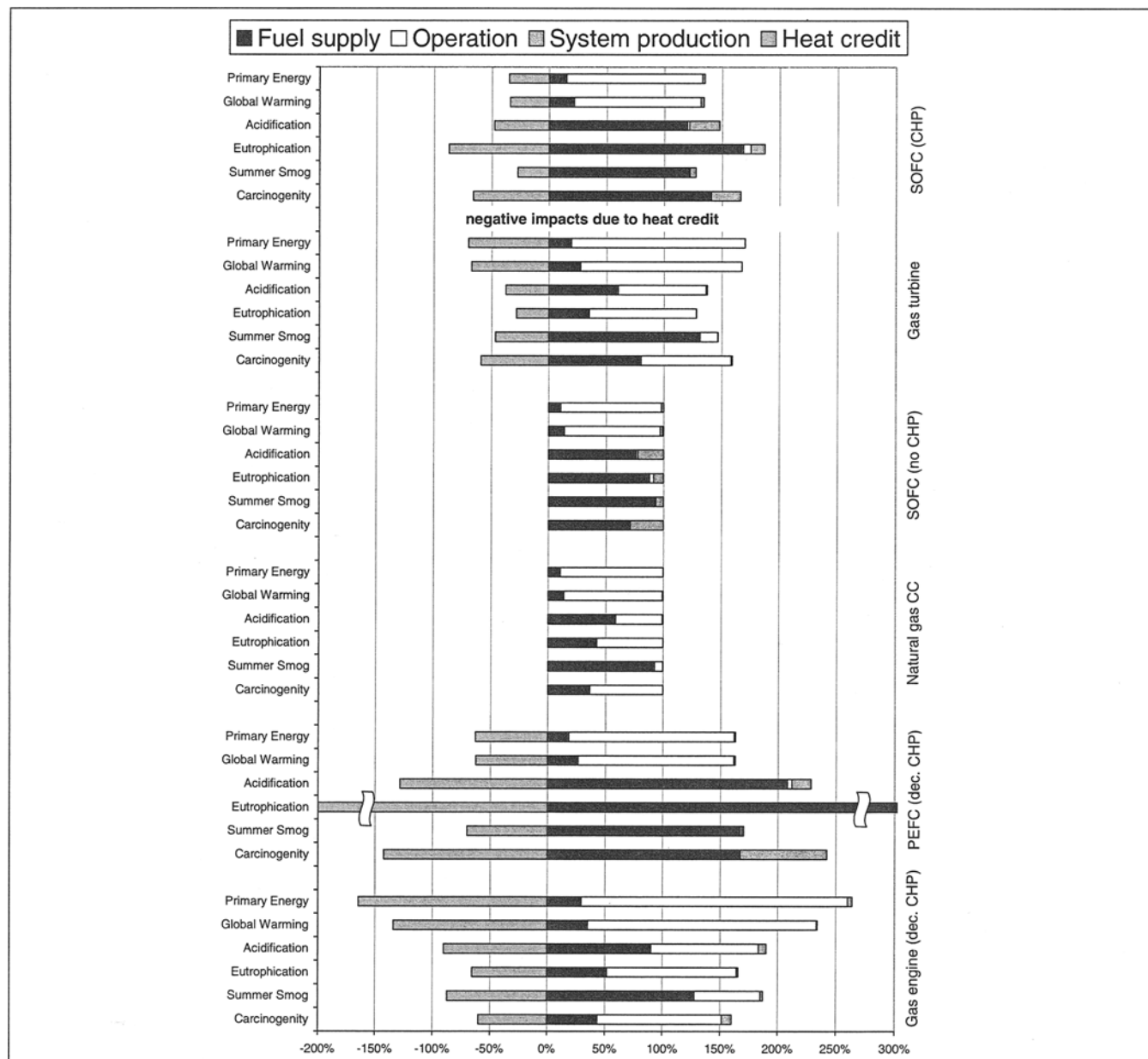


Fig. 6: Contribution of life cycle stages to total environmental impacts to the systems of Fig. 5. Bars are scaled in such a way that positive impacts minus heat credit yield 100%

cogeneration. Independently of the conversion technology, CHP proves to be superior to pure electricity production due to the use of the exhaust heat. Therefore, combined heat and power production should generally be promoted. In addition, not only the electrical, but the total efficiency needs to be optimised. However, the development of high-efficiency centralised electricity production based on fuel cells decreases the gap between cogeneration and non-cogeneration plants.

Due to the higher life-time of the power plants, their production is of much less relevance than in the case of mobile systems (Fig. 6). LCAs can point to potential ecological weak points of the production, such as, for instance, the use of chromium and the high electricity demand for sintering and electrochemical etching in the planar SOFC production process. On a life-cycle basis, however, the infrastructure, i.e. the production of the fuel cell power plant, is of almost no significance for global warming and contributes less than 20% to the life-cycle acidification. This can be seen from Figure 6 where the contribution of the life cycle stages to total life cycle impacts are shown. For acidification, the relative contribution of production is higher because of the low absolute emissions contributing to acidification. In addition, these emissions depend on the system design chosen. In this particular case, the emissions are caused by the electricity for production (e.g. sintering the membrane-electrode assembly and electro-chemical etching of the interconnects) and the chromium for the planar interconnects. For a more detailed analysis of the contribution of the materials and production steps of fuel cell production see (Pehnt 2002a).

3.6.2 Systems operated with biofuels

The use of biofuels in fuel cells combines the low direct emissions with extremely low resource consumption and greenhouse gas emissions. Therefore, a second example compares an SOFC using synthesis gas from wood gasification with a gas turbine using the same gas and the future (2010) German electricity mix (Fig. 7). It can be seen that the pri-

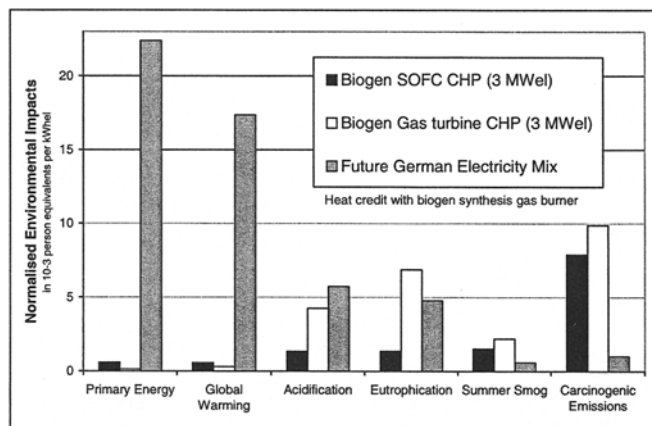


Fig. 7: Normalised results of LCAs of different electricity generating systems converting synthesis gas from gasified wood in a SOFC and a gas turbine compared to the future (2010) German electricity mix (functional unit: 1 kWh_{el}). If heat is coproduced it is credited with a modern gas burner using the same synthesis gas ('avoided burden'). All data is normalised to person equivalents by dividing the impacts by the average daily per capita impact in Germany (see Figure 5)

mary energy demand and the greenhouse gas emissions can be drastically reduced by both the SOFC and the gas turbine. The advantages of fuel cells when coupled with biogen fuels are, on the one hand, the more efficient use of the often restricted biomass potentials and, on the other hand, avoiding an increased emission level which is typical for many other biomass based energy converting systems. In addition, low heat-to-power ratios are advantageous if the external heat demand is limited, as is often the case in biogas plants.

4 Conclusions

Fuel cells are promising energy converters for mobile, portable and stationary applications. Depending on the fuel cell technology, the application area, the input fuel and the baseline technology, mainly environmental advantages, but also some disadvantages can be expected (Table 4). In addition, selecting the fuel is generally of higher environmental relevance than the energy converter.

In mobile applications, fuel cells offer advantages in many impact categories. However, the competition of conventional competitors is getting stronger due to the developments of more stringent emission legislation and strict requirements regarding fuel consumption. The fuel consumption, or more exactly the fuel economy ratio (fuel consumption ICE/fuel consumption fuel cell) is the crucial parameter and still needs further, particularly empirical investigation in pilot cars. Compared to future ICE vehicles and based on fossil primary energy carriers, greenhouse gas reductions in the order of 15% (hydrogen from natural gas) or 0% (methanol from natural gas) can be achieved. Analysing more dynamic driving cycles than the NEDC, the greenhouse gas advantages of fuel cell vehicles would be further reduced (Pehnt 2002c).

For global warming and energy resource consumption, the fuel has a larger significance than the particular power train. Renewable fuels such as solar hydrogen lead to reductions of 70 to 90% compared to the gasoline option regardless of the power train. For such fuels, ICE and fuel cell vehicles exhibit similar global warming results. The lower fuel consumption – and thus upstream greenhouse gas emissions – are slightly more than offset by the higher impacts from vehicle production.

It has to be noted, however, that under the assumption of a solar hydrogen scenario, fuel cell vehicles exhibit further, more techno-economic advantages, such as a lower hydrogen demand and associated advantages (possibility to use gaseous hydrogen storages instead of liquid hydrogen; lower fuel costs; higher mileage from limited renewable energy carrier potential).²

² The question whether the allocation of renewable energy carriers to the transport sector are ecologically 'efficient' (e.g. in terms of greenhouse gas reduction) compared to using these primary energy carriers in power production instead is discussed (Pehnt 2001a).

Table 4: Comparison of fuel cells operated with different fuels to competing technologies (time horizon: 2010)

		Primary energy ¹	Global warming	Acidification	Eutrophication	S-Smog/ NMHC	Carcinogenity	Competitor
PEFC mobile (passenger car)	H ₂ fossil	+	+	++	++	++	++	ICE (Gasoline, Euro 4)
	H ₂ reg.	++	++	+ / ++ ²	++	++	++	
	MeOH fossil	-	o	+	++	++	++	
	MeOH reg.	++	++	- ³	- ³	o	- ³	
	MeOH fossil	+	+	++	++	+	++	Methanol DI fossil
	MeOH reg.			+	+	+	+	Methanol DI reg.
PEFC stat.	Nat. gas	-	o	++	++	+	++	Nat. gas engine CHP
SOFC	CHP, nat. gas	+	+	++	++	+	+	GT (nat. gas)
	CHP, biomass	o	o	++	++	+	+	GT (biomass)
	central, nat. gas	+	+	+	++	+	+	Nat. gas CC

++ great advantage, + advantage, o neutral or not significant, - disadvantage, -- great disadvantage

GT gasturbine, ICE internal combustion engine, Euro 4 advanced european emission standard (2005), DI direct injection, CC combined cycle

¹ only non-renewable. ² ++ for compressed H₂. ³ strongly depending on process and competing system. Large improvement potential

lower data quality

Rather than ecological aspects, further advantages could promote the introduction of this power train including the compatibility with drive-by-wire or autopilot technologies, innovative safety concepts that can be realised with electric vehicles, and higher user comfort and acceleration.

In industrial combined heat and power production (CHP) and central electricity production, Solid Oxide Fuel Cells (SOFC) are in almost all impact categories superior to both conventional competing technologies and the future (2010) German electricity mix. The use of non-renewable energy resources and the global warming are reduced by approximately 10% compared to conventional modern technologies and up to 45% compared to the electricity mix. In decentralised CHP for district heating applications, however, the climate advantage compared to the competing reciprocating engine is not existent because of the lower overall efficiency of fuel cells. Therefore, focus of future development of fuel cell power plants should be on increasing the thermal efficiencies.

In the case of local emissions and related impact categories (e.g. acidification), fuel cell power plants in all stationary applications allow considerable reductions compared to separate electricity and heat production as well as compared to competing CHP systems. Unlike engine CHP plants, fuel cells couple the advantages of reduced energy consumption with low direct emissions.

5 Outlook

The future development will bring some radical changes with respect to materials, concepts and applications, but also with respect to the framework – deregulated electricity markets,

increasing pressure on climate policy or emission control, etc. – in which fuel cells have to be established. Therefore, LCAs at such an early stage of the market development can only be considered preliminary. For instance, it is still not clear that it will be possible to realise the efficiencies as assumed here for fuel cell systems. LCAs help to recognise ecological weak points or bottlenecks, such as critical materials (e.g. catalysts, graphite, chromium), process steps (stack sintering) or parameters (thermal efficiencies, fuel economy ratio), and to gradually improve process and system development. In a current project, LCAs of further stationary fuel cells, including Phosphoric Acid and Molten Carbonate Fuel Cells, and smaller systems, such as domestic MicroCHP systems, are assessed. The results of these LCAs will be subject of a future publication. Due to the rapid technology development it is an essential requirement to accompany the ongoing research and development with iterative LCAs and help decision makers as well as companies to make decisions under the constraint of limited information on power plant and power train technologies, fuel options, materials or operating conditions.

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